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13. ABSTRACT *(Maximum 200*

This project involves the development of surgical simulators for training military and civilian personnel in critical trauma procedures. In this context, a virtual reality simulation of the "Shattered Kidney" surgical procedure is being produced using new technologies in computer graphics and physically-based modeling. The objective of this effort is to provide a degree of training and evaluation of performance that is not possible using existing technologies in trauma surgery in the battlefield and emergency room.

A major focus of the first year of the project has been the development of software functionality that can be used to author the "Shattered Kidney" simulation. The authoring package being developed by High Techsplanations, Inc. (HT) is called Teleos™, and is designed to produce interactive simulations with tissues and organs that display appropriate physical and physiological behavior. Features needed for the simulation include cutting, bleeding, suturing and real-time tissue deformation. A virtual abdomen is being built from the Visible Human dataset to provide an accurate anatomical rendering of the structures involved in the procedure. The fully developed simulation will allow a user to perform the "Shattered Kidney" operation with all of the visual, haptic and cognitive components of the actual surgical procedure.

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FOREWORD

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TABLE OF CONTENTS

I. INTRODUCTION

A. Objective

The objective of creating a computer simulated virtual environment for medical training is to provide a level of training not possible using traditional methods. In this project, we are developing the software tools and the medical content to produce a virtual reality simulation of the surgical removal of the "Shattered Kidney", complete with all of the visual and haptic features of the actual surgical procedure. This procedure is a critical component of trauma management in the battlefield setting, where massive blunt or multiple penetrating injury requires the surgical removal of part or all of the kidney (nephrectomy). In addition to the procedure itself, special tracking protocols will be embedded in the application, so that the performance of individual users can be evaluated, and compared to a database of normative values.

B. Background

Traditional techniques for teaching trauma procedures have depended largely on the existence of a sufficiently large number of proctors with adequate surgical skills to teach trauma procedures. Other approaches include practice on animals, but animal models of injury often do not reflect human trauma, and raise a host of ethical issues concerning procuring and maintaining animals for surgical training. Also, practice on humans and animals precludes the ability to repeatedly rehearse specific components of the procedure that may prove challenging or require finely tuned motor skills. An additional concern is that Department of Defense (DoD) hospitals are usually not regional trauma centers, so that physicians and allied health personnel in the military may not obtain significant exposure to human trauma cases for training purposes.

Although the airline industry and DoD have used flight and battlefield simulators for many years, several technical challenges have limited the use of computer-based simulation technology in medical education. A flight simulator is easier to implement than a surgical simulator; the terrain of the ground is fixed and rigid, and an airplane simply moves through a path above this terrain. A surgical simulator, on the other hand, is more complex. The terrain of the body (the internal organs) must be interacted with, and they must flex, be able to be cut and then re-attached. This manipulation involves much greater computational sophistication. The organs in the body must be programmed with physiological behaviors and basic principles of physics so they respond appropriately when they are cut, tugged, and stretched. In addition, the surgical simulator must have knowledge of how each instrument interacts with the tissues. For example, a scalpel will cut tissue when a certain amount of pressure is applied; however, a blunt instrument may not– this fact must be simulated.

Virtual reality technology holds tremendous promise for surgical trauma training, because it offers physicians, battlefield and emergency medical personnel the opportunity to practice in an environment where mistakes do not adversely affect patients. An optimal training simulator accurately replicates the physical and physiological properties of the real procedure. In addition, it offers the ability to automatically track and evaluate performance, provides the option of different procedural scenarios, as well as simulating a range of surgical complications and anatomical anomalies.

Computerized surgical simulations will make a tremendous impact in improving surgical morbidity and mortality. Studies have shown that, for a wide range of diagnostic and therapeutic procedures, doctors doing their first few to several dozen cases are much more likely to make a greater number of errors. Adequate proctoring of learners by experienced surgeons is cumbersome, as there are few surgeons experienced enough in the techniques to proctor their colleagues. It is exceedingly difficult, for physicians, particularly those in rural areas, to travel to larger medical centers for training. The requirement also places a burden on experts who could become overwhelmed with proctoring requests.

C. Technical Goals and Experimental Approaches

The goal of this project is to make the "Shattered Kidney" simulator as realistic as possible for a positive training experience. Realism in the context of virtual environments for medical training relates to how the anatomical structures appear, how life-like the interaction is with the anatomy, and how it behaves when one interacts with the anatomy. To accomplish this goal, the first requirement is the development of software that can produce anatomically accurate models that display the physical and physiological characteristics of living tissues.

<u>The first technical goal of the project is to develop a software authoring environment in which physical attributes can be integrated into the anatomical models, virtual surgical tools and input device, so that all behave in an appropriate manner</u>. This involves examination of the surgical procedure to identify those actions that require enhancement of the current technology, such as cutting, clamping, grasping and suturing, as well as specification of the normal behavior of the tissue. New algorithms and physical solutions are needed to simulate all of these actions. The general approach is based on advances in 'physically' or 'physics-based' modeling, as articulated by Barr and his colleagues (see Barzel, 1992).

The abdominal virtual environment is created from the magnetic resonance imaging (MRI), computerized tomography (CT), and the photographic dataset of the Visible Human Project (National Library of Medicine). The surgery scene consists of several types of entities including physically-based tubes,

polyhedra, volumetric data, and particle systems. Tubes are the primary entity of a simulation and embody a spatial spline formulation having the properties of Newtonian physics. They have the ability to be deformed in real-time through contact with tools, other tubes, and additional forces. Tubes can be developed from the medical imagery templates as well as independently created. Polyhedra are non-deformable objects that may be imported from standard file formats and manipulated to be properly scaled and placed into the surgical scene. Volumetric data is derived from the same imagery used for templates and can be used to view the interior of objects by taking advantage of the 3D volume texture rendering capabilities of Silicon Graphics workstations.

Once the geometry of a surgical scene has been defined, the interconnections between the objects and the physical properties of the tubes are specified. Surgical tools are selected from a group of previously created tools or a new tool can be created. Lastly, the simulation designer refines the response of the simulation by testing and adjusting the interconnections and their properties. Once a simulation is complete all that needs to be provided to the trainee is the data describing the scene and the simulation engine. The simulation engine allows a simulation to be paused or saved for later use. The activities of the simulation user can also be saved for later review. An additional feature of the simulation engine is the ability to save 'snapshots' for the simulation in progress that can be viewed with the recently developed 3D Internet web browsers.

The second technical goal of the project is to add functionality to the software authoring environment so that physiological characteristics of the tissue can be modeled. Once the 3D models have been created from 2D image sources, one of the biggest challenges for surgical simulation is creating organs that exhibit the physiological characteristics of living tissues. These properties include intrinsic, ongoing autonomic functions such as peristalsis of the gastrointestinal tract, and physiologic responses to extrinsic perturbation of tissues by cutting, grasping and pulling with surgical instruments.

Among the feature set under development in the software authoring toolkit, we have included the following physiological characteristics:

(1) Localized Irritability - This is a general property of most organs, and consists of a localized contraction of the surface ('twitch') in response to being touched or prodded. This response is greater in reaction to metal instruments, because the response is electrophysiologic in nature (mediated by local neurons or muscle cells). Other localized responses include bleeding following cutting or damage caused by other tissue manipulations.

(2) Reflexivity -

This covers a magnitude of responses that are mediated by reflex circuits that travel through the central nervous system. One example is the contraction of a muscle after being grasped and pulled. Almost all tissue responds to painful stimuli with a variety of actions, such as withdrawal from the stimulus, and may exhibit more global responses, which at a local organ level would be manifested by an increase in pulse rate and respiratory movement.

(3) Contractility -

This is a feature of muscle (cardiac, smooth and skeletal). One obvious example is the rhythmic contraction of the heart, which produces the pulsatile pressure wave in blood vessels (the magnitude of the pressure wave is greater in arteries than in veins).

(4) Respiration -

A property of the respiratory system, which can be rapidly modified by external stimuli such as exercise and painful stimuli. Respiration, like heart rate, is an ongoing phenomenon which is obvious at the local organ level.

(5) Peristalsis

This list is not exhaustive, and other local and global physiological properties are being added to the repertoire of templates and functions during the ongoing evolution of the software authoring toolkit.

<u>The third technical goal of the project is the integration of all physical and physiological functionality with the medical content of the "Shattered Kidney" procedure to produce the virtual reality simulation</u>. Once the software features of the authoring toolkit have been developed, a full treatment of the "Shattered Kidney" procedure will be authored, in concert with medical consultants such as Dr. Howard R. Champion, Director of Trauma Surgery at the Uniformed Health Sciences University. Storyboards will be prepared from the procedural script, and all of the virtual reality and interactive multimedia elements will be implemented based on this design. Hypermedia elements will include audio cues such as 'Warnings' when mistakes are made, and text screens providing case presentations and reference information. Performance tracking software will be embedded into the procedure to measure timing and accuracy of individual users. The performance assessment will be configured to provide both individual feedback to the trainee, as well as administration by a mentor or supervisor. Performance media elements will include registration, administration and outcome analysis screens.

II. BODY

A. Technology Development for Trauma Simulation

Much of the first year's efforts have been directed towards building programming tools that will allow us to produce a completely realistic, interactive abdominal simulation of the "Shattered Kidney" procedure. The rapid pace of technological innovation in graphics and physically-based modeling has led us to concentrate on the creation and optimization of programming tools and libraries, and has prompted us to devote most of our efforts in this arena prior to the full implementation of the "Shattered Kidney" simulator. A software authoring toolkit is being developed that allows both the programmer and the non-programmer to produce interactive, physically-based simulations using pre-determined or customized medical content. Models can be built from scratch, or derived from sequential 2D imagery such as CT, MR and the 'Visible Human' dataset. The architecture consists of simulation design and simulation engines for the creation and manipulation of virtual environments. The software uses OpenGL and OpenInventor, and is configured to run on Silicon Graphics, Inc. (SGI) workstations. The interface is designed to accept 'force-feedback' and passive input devices for a wide variety of procedures, ranging from endoscopy to minimally invasive surgery.

(1) Progress Report

We have made progress on the following tasks within the first year of the project period:

Planning Tasks

- Assess open kidney repair surgical procedure for exact actions
- Survey of existing simulation technologies
- Assessment of software enhancements needed to perform actions
- Evaluation of algorithmic and coding solutions for software enhancements
- Identification of subsections of full surgical procedure

Code Implementation Tasks

- Rearchitecting software authoring toolkit
- Surgery simulation authoring software tools
- Surgery simulation interaction application
- Tools to create anatomic geometry from Visible Human data set
- Tools to create realistic textures for anatomy
- Integration of force feedback equipment with the simulation code

Surgery Content Development Task

- Creation of normal anatomy for open kidney procedure simulation

Our primary accomplishments this past year related to the development of software tools for the "Shattered Kidney" procedural simulator have included:

Planning Tasks:

- Assessment of the "Shattered Kidney" surgical procedure for exact actions

A full literature survey coupled with consultation with trauma surgeons have been undertaken to identify the set of specific actions required to perform the "Shattered Kidney" procedure. The deliverables for this component, due by February 1996, include:

- Procedure description and script
- List of physical tasks to be simulated
- List of anatomical structures involved in procedure

- Survey of existing simulation technologies

A broad market survey of available simulation development software is underway. New technologies are being evaluated to determine any existing tools that can be used to help create the "Shattered Kidney" procedural simulation. Spatial tracking and force feedback devices have been evaluated to find most applicable interface devices for simulation. Computer hardware developments including CPU's, dedicated graphics display boards, and operating systems have been evaluated as part of this process. This survey will remain as a continuing effort throughout the project to assure that the most effective technologies are being used. The deliverables include update reports internally of software and hardware technologies

- Assessment of software enhancements needed to perform actions

After assessment of the physical tasks associated with the "Shattered Kidney" procedure, we have identified a set of actions that cannot be satisfactorily simulated by the current software algorithms. These actions have been broken down into specific features that must belong to the different objects simulated within the software authoring environment.

New actions to be simulated include:

- unstructed cutting of deformable tube objects
- bleeding - fluid modeling using particle systems
- fine and blunt dissection
- suturing
- ligation

- vascular clamping
- modeling of physiological events, including arterial pulsation and intestinal peristalsis

- Evaluation of algorithmic and coding solutions for software enhancements

As new features are to implemented, the applicable literature has been surveyed to evaluate previous related algorithmic approaches. Either previous algorithms have been adopted or new solutions have been derived as needed. In each case the feature has been converted into implemented code. The deliverable for this evaluation component will be a report to be generated by the end of October 1996.

- Identification of subsections of full surgical procedure

The "Shattered Kidney" procedure has been broken down into smaller subsections. These subsections are being prioritized based on the complexity of the simulation task in relation to the existing capabilities of the software authoring environment. The purpose is to produce simulations of parts of the procedure that are easier to simulate early on in the project so that there is a series of demonstrable results throughout the project.

The major subsections include:

- cutting open the abdominal wall, retraction
- abdominal exploration
- fine dissection of major vessels and tissue planes
- vascular clamping
- colon resection
- kidney repair

<u>Code Implementation Tasks</u>:

- Rearchitecting software authoring toolkit

The current architecture of the algorithms and code in the software authoring toolkit has been assessed and we have determined what must be changed and how this must occur. The total rewrite of the existing simulation code is driven by the need to make the code upon which the open kidney procedure simulation to be:

- Robust- will not fail during simulation, will always behave in an expected manner
- Generalized- capable of simulating other surgeries more easily in the future
- Open ended- no impediments to future enhancements to the simulation abilities
- Platform independent- capable of being moved to more cost effective hardware

The deliverable for this component will be the new version of core code implementing all the above principles.

- Surgery simulation authoring software tools

Taking the core simulation code, an application is being created that allows a non-programming user who is or has access to the medical content experts to create their own surgery simulation. This will enable HT as well as future users to produce a variety of simulations more rapidly without having to master a variety of computer and mathematics skills. To enhance its usability, the program will be compliant with the graphical user interface of the platform on which it is running. The deliverables for this component of the project will be the software design authoring package for the SGI workstation family.

- Surgery simulation interaction application

Taking the same core simulation code used by the authoring program, a program is being developed that uses the surgery simulation content created by the authoring program to allow a trainee to carry out a surgery simulation. This program will be a stand-alone program that does not require special computer skills to perform the surgery. The user will work with interface devices that allow them to work in the manner they expect, e.g. hold a scalpel not a mouse to cut a tissue in the simulation. This application will initially be implemented on Silicon Graphics workstations. Toward the end of the project an attempt will be made to implement this on a more consumer oriented platform and operating system such as a Pentium machine with dedicated graphics accelerator and Windows NT. The interface between the user and the computer will be a general spatial tracking and force feedback device that can be used for all the tasks of the procedure. The deliverable for this component is the interactive simulation engine for the SGI workstation family.

- Tools to create anatomic geometry from Visible Human data set

Specific tools are being added to the software authoring toolkit to enable the user to create the geometry of the needed anatomy for the "Shattered Kidney" procedure from the Visible Human data set of the National Library of Medicine. In addition, these tools will allow the user to take other data, such as MR and CT scans, and use this to create the geometry. Enhancements of these tools, which will be developed by HT, will be added later in the project as they become available from our subcontractor, SRI International. The deliverables for this component include:

- Initial manually controlled software tools
- Enhanced tools incorporating semi-automated techniques

- Tools to create realistic textures for anatomy

Tools are being developed to create photorealistic texture maps for the anatomic structures used in the simulation. These tools will allow us to create detailed surface features that provide visual cues required to effectively navigate the surgical field during the procedure. Commercial 3D paint software will be adapted if something with the appropriate features can be found, otherwise we will develop our own software and use the color information contained in the photographic data of the Visible Human data set to guide the creation of the anatomy coloring. The deliverable for this component is a fully functional surface painting software module for Teleos.

- Integration of force feedback equipment with the simulation code

The current force feedback technology has been evaluated and we have determined that the PHANToM (SensABLE Devices, Cambridge, MA) is the most appropriate device for use with the "Shattered Kidney" procedural simulation. A cooperative development partnership has been established with SensABLE Devices to ensure that the device's capabilities and its software interface fully meet our simulation requirements. A prototype application has been developed to test out deformable object algorithms with a force feedback device. The device has been integrated into the simulation interaction application built upon the core code so that force feedback can be available in any authored simulation. The deliverables for this component of the project include:

  - Prototype of demonstration of force feedback with a deformable object
  - Full integration of force feedback into Teleos simulation interaction application

<u>Surgery Content Development Tasks</u>:

- Creation of normal anatomy for open kidney procedure simulation

The Teleos authoring software and the software developed by its subcontractor, SRI International, have been used to create anatomy needed for the simulation from the Visible Human data set (please see page 15 for more details). This anatomy will be delivered in stages with only the amount being created that is appropriate to the subsections of the entire procedure being simulated at a given time. The data includes the geometry of the anatomy as well as the surface coloring/texture information. The deliverables for this component of the project are multiple sets of anatomy delivered for each subsection of the procedure.

(2) Software Feature Set

The software design authoring environment has been created for the non-programmer who has some facility with graphics applications that run on SGI machines. This individual most likely works in a medical school, university, hospital, medical research laboratory or commercial environment as a medical content developer. The extensive use of 'scripting' and object-oriented design allows the developer to rapidly assemble procedural simulations.

Importing files from other applications: In addition to the native file format, a number of popular 3D file formats will be supported by the software authoring environment, specifically Inventor™ (SGI) and its subsets (e.g., VRML). Inventor™ contains a file translation program to convert other files into the Inventor format. For example, Silicon Graphics Object (SGO)™ data files can be translated into Open Inventor™ files using the translator.

Modeling and model attributes: The Modeler program contains several functions for importing models, building models, texture mapping, adding multimedia components such as audio, timing functions, viewing functions, assigning physiological properties and attaching physical properties. Deformable models are built and manipulated in the context of the Modeler. Physical characteristics such as stiffness, mass and damping can be assigned to the models. Other tools are available for building 3D models from 2D images (accepts all popular 2D image file formats). Each model is assigned its own attribute list, including collision parameters, intrinsic physics, texture, etcetera.

The Blood Source Builder assigns bleeding and blood attraction and repulsion attributes. It contains a flow rate slider, bleeding delay control, color wheel (e.g., for distinguishing between arterial and venous blood) and cut shaping functions. Blood attractor and repulsor points can be placed at any location in the virtual environment, and have a slider control for strength and polarity. The Visual Features Module allows importation of 2D texture maps, assigns built-in textures including bone, cartilage, artery, vein, muscle type (skeletal, cardiac, smooth), nerve (CNS, PNS, white matter, gray matter, choroid plexus, meninges), intestine, liver, spleen, pancreas, kidney, lymph node and tissue, urinary tract, reproductive tract, respiratory tract (lung, bronchi), skin, fascia, connective tissue and adipose tissue, among others. Additional texture mapping controls include placement and specular effects. The ViewWorld Module includes all features necessary for viewing models, including scene lighting and cameras. The Timing Module includes event-driven phenomena, such as clocks that can triggered for each object and event. Pop-up text dialog boxes can also be linked to objects when events occur, for example, this will allow the designer to assign a text "WARNING" with explanation to a mistake event. The Audio Recorder Module allows the user

to record sound bites and assign them names for use in the World Sequencer (see below). All the events are controlled and scheduled using the Sychronization Module.

Building virtual environments: The GUI Driven World Sequencer allows the designer to import models and establish relationships between models to build the completed virtual environment. Connective elements such as springs can be used to tie models together and constrain their movement. It also allows assignment and queuing of up to 4 audio tracks. Active manipulators can be selected from 7 choices - scissors, retractor, forceps, knife (includes scalpel), probe, autosuture and clip/clamp applier. Scripting capabilities are also available for added functionality.

Input device integration: The Device Interface Integrator allows the designer to select the interactive device to be used when a new environment is opened up. Supported devices include mouse (default), PHANToM (SensABLE Devices), Immersion laparascopic tools and endoscope (Immersion Laboratories) and the Polhemus Fastrack.

Other: Features include standard edit functions (cut, copy, paste, save, save as, etc.), display options (stereo or monaural) and on-line help.

(3) Software Architecture

The software authoring toolkit is a development environment for developing production quality software for interactive simulation of surgery. Typical scenarios in surgical simulation include human organs - such as skin, urinary tract, heart, lungs, arteries, veins, blood -and the results of their interaction with surgical devices, such as rupturing of skin and tissues, cutting of arteries and veins and blood flow as a result of that, deformation of the surface on contact with the device. The software's approach to this challenge is through physically-based modeling of flexible rigid bodies. Physically-based modeling incorporates physical characteristics into models, permitting mathematical simulation of their behavior [Barzel, 1992].

The architecture is driven by the potential packages and programs (Stand Alone Projects or SAP's) that will be developed on top of the system. Internally it is a set of efficient and highly reusable C++ classes built over IRIX, OpenGL and XLib/Xt/IM. For ease of implementation, the authoring toolkit has been conceptually divided into two parts: HtTypes Library and Primitives Library. Built on top of these will be the packages that can be used for surgery simulations by customers.

HtTypes Library is a library of classes which are independent of OpenGL and X, and includes vectors, matrices, etc. The Teleos Primitives Library is built on top of HtTypes Library, OpenGL, and XLib/Xt/IM. The software packages built using the software authoring toolkit are referred to as Stand Alone Projects.

An example of an SAP is the "Shattered Kidney" simulator that is being developed for the present project.

B. "Shattered Kidney" Abdominal Simulation

A "Shattered Kidney" formally refers to multiple lacerations of the kidney with contained or disrupted fragments, often held together by the remains of the renal capsule (McAninch and Carroll, 1989). This usually results from severe blunt or penetrating trauma to the kidney. McAnnich and Carroll (1989) provide the standard method for classifying the extent of renal trauma. Among civilians, 80% of all renal trauma is due to blunt trauma, with motor vehicle accidents accounting for the vast majority of cases (Chambers, Champion and Edson (1989). Although the kidneys are well protected by the ribs, vertebrae, back muscles and abdominal viscera, they are the most commonly injured organs in abdominal trauma. In the battlefield setting, the "Shattered Kidney" can be caused by extensive penetrating wounds, such as caused by bullets or shrapnel, or by massive blunt trauma. In both the emergency room and in the battlefield, the best approach for the "Shattered Kidney" is rapid complete or partial nephrectomy (Guerriero, W.G. and M. Coburn (1994)).

(1) Procedure (adapted from Taylor, D.L. and W.R. Fair (1985))

Major indicator of serious complications: Loss of continuity of the renal capsule and distraction of fragments.

If visualized or suspected, major perirenal hematoma indicates the necessity for opening of the retroperitoneum and exploration of the kidney. In the emergency setting, injudicious exploration may lead to unnecessary nephrectomy, however, several studies have shown the first 2-3 days offer the best window of opportunity for corrective surgery.

Surgical approaches:

(1) Make a vertical midline incision in the abdomen.

(2) Begin exploration of the abdomen, following establishment of hemostasis - include debridement of the path of any penetrating object(s) or missile(s). The retroperitoneum is approached along the aorta at the root of the mesentery.

(3) If you find the existence of a large retroperitoneal hematoma or other indications of a major renal trauma, open the retroperitoneum medial to the inferior mesenteric vein and identify the aorta.

Indications for surgical exploration of major trauma (McAninch and Carroll (1989)):

- Expanding or uncontained hematoma
- Pulsatile retroperitoneal hematoma
- Major urinary extravasation
- Non-viable renal parenchyma (loss of more than 15% of the kidney)
- Vascular injury

Please note that some of these indications can only be determined using pre-operative imaging methods, which may not be practical in a battlefield setting.

(4) Dissect cephalad along the anterior surface of the aorta to expose the left renal vein crossing the aorta.

(5) Vascular control is obtained by clamping the renal vein and artery at their origins from the vena cava and the aorta. (mistake possible here - if the surgeon strays too far cephalad and lateral to the aorta, the splenic artery and vein may be mistaken for the left renal artery and vein).

(6) Reflect the colon prior to exploration of the retroperitoneal space.

(7) Use the principles of exploration outlined by Scott and Carlton and their colleagues (Scott, Carlton, and Goldman (1969); Scott and Selzman (1966):

- Obtain early vascular control
- Debride any devitalized tissue
- Obtain hemostasis by suture ligation
- Insure watertight closure of the collecting system
- Approximate the parenchymal margins
- Obtain extraperitoneal drainage of the renal fossa

(8) Analysis/corrective surgery of the kidney:

Substantive damage limited to a portion of the kidney usually indicates partial nephrectomy.

Disruption of the collecting system usually occurs through damage to the calyceal fornices. This repair involves watertight suturing of the collecting system at the level of the fornix.

If bilateral renal damage is present, the kidney with the best possibility of recovery is repaired first.

Transcapsular damage is often present in major renal injuries, especially those with penetrating injuries (eg, bullets, shrapnel; see Scott, Carlton and Goldman (1969)). In these cases:

- Ligate all major vessels.
- Use a watertight closure for the collecting system.
- Close the capsule with running or interrupted sutures.
- Use diverting pyelostomy for clots in the renal pelvis.
- Make sure that all devitalized tissue is debrided.

(2) Simulation issues

(a) Overview

The "Shattered Kidney" procedure presents several technical challenges for medical simulation. First, it is an open field surgical procedure, so that cutting open of the abdominal wall will be one of the first steps in the procedure. Cutting, retraction and finally suturing closure will have to be simulated. Second, arteries and urinary tract components may have to be ligated, which involves a high dexterity, two-handed motor manipulation. Finally, the actual nephrectomy involves the extensive cutting and removal of a large amount of tissue, necessitating handling of large tissue masses within the context of the simulation (i.e., mediated by the input device(s)).

A script and storyboards for the simulation are under development. In addition to the technical challenges in physically-based as outlined above and solved as part of Teleos development, interactive multimedia elements are being added to serve as audio and text cues for the user of the simulation. These include "Warning" cues to notify the user when mistakes are made, or when a component of the procedure is taking longer than appropriate. Finally, performance tracking and management software is being developed to aid in the evaluation of user performance. The emphasis is on timing and accuracy of motor manipulations, and on cognitive aspects of the simulation. Registration, administration and results screens will allow the user, or test administrator, to evaluate the performance of an individual user and compare his or her performance to a database of expert and novice users.

(b) Extraction of the Visible Human data for abdominal modeling

One of the tasks that has been completed is the creation of models of abdominal organs for the "Shattered Kidney" procedure. The normal anatomy has been extracted from the "Visible Human" dataset obtained from

the National Library of Medicine, National Institutes of Health. The ultimate goal of the Visible Human Project was the acquisition of CT and MRI images, and high resolution photographic images of transverse cryostat sections, from a representative male and female cadaver at a resolution of one millimeter or greater. The Visible Male data set is approximately 15 GB, and was obtained from the NLM.

Dr. Harlyn Baker, Senior Computer Scientist at SRI Interanational, has developed automated approaches for extracting and segmenting the abdominal anatomy for the "Shattered Kidney" simulation, as part of the subcontract component of this grant. Several anatomical reconstructions have been made with the cross-sectional photographic images. These images are 2048 X 1216 pixels in size in 24 bit color. 3D models are being derived from this data set through the process of polygonalization. A mesh is created from the high resolution color data, and the points define the vertices of the polygons. Anatomical regions that have alot of detail are represented by a denser meshwork of polygons. Once the polygonal mesh has been created for a given 2D section, it is aligned over consecutive sections to create a 3D model. The process of alignment (called registration) is not trivial, since even a small amount of mis-registration may cause spatial breaks in small objects such as blood vessels. Once the 3D model has been created, it needs to have other features such as physical properties and texture maps added to the spatial framework. Finally, the model needs to be manipulated in such a way that it will provide a realistic simulation of a surgical procedure or anatomical demonstration. All of these events, from 3D model building through surgical simulation, are achievable in the context of the software authoring toolkit.

III. CONCLUSIONS

The following conclusions can be drawn from the first year of the project:

(1) The development of appropriate software tools is critical to the success of the project. We have developed a software authoring environment in which it is possible to author interactive, physically-based simulations with the physiological realism necessary to simulate a procedure as complicated as the "Shattered Kidney". Within the context of this software, specific technical challenges, including cutting, blood flow, suturing, tissue deformation, and force-feedback appropriate for the "Shattered Kidney" procedure are being addressed and resolved. Future progress depends on a combination of algorithmic and graphics computing solutions to resolve demanding components of the procedure.

(2) The PHANToM input device will be used as the appropriate equipment interface for the simulation, because it offers the greatest degree of control and sensitivity available on the market. It is being programmed to provide appropriate levels of force feedback and haptic sensitivity for the procedure.

(3) Appropriate levels of anatomical detail for abdominal structures has been achieved using the "Visible Human" dataset which has been obtained from the National Library of Medicine. The photographic image resolution is high enough for the most detailed features of the simulation, and the dataset can be decimated (reduction of complexity) for portions of the simulation that require higher speed and less detail.

(4) The educational and instructional design issues relevant to the "Shattered Kidney" simulation have been identified and addressed in the context of the simulation. The most important features to be implemented in the future are: (1) acquisition of appropriate motor and cognitive skills by the user of the simulation, and (2) software recognition of user error using embedded performance measures.

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V. APPENDIX

A. Publications

Merril, J., Merril, G., Raju, R., Millman, A., Meglan, D., Preminger, G., Roy, R., Babayan, R., "Photorealistic Interactive Three-Dimensional Graphics in Surgical Simulation," Interactive Technology and the New Paradigm for Healthcare, Vol,. 18, p. 244-252, 1995.

Merril, G., Raju, R., Merril, J., "Changing the Focus fo Surgical Training: The World's First VR Laser Iridotomy Simulator," VR World Magazine, Vol. 3, No. 2, p. 56-61, March/April 1995,

Merril, J., Higgins, G., Raju, R., Milman, A., Roy, R., Merril, G., "A Virtual Reality Swiss Army Knife: An Authoring System for Developing Everything from Neurosurgical Training Applications to Video Games," VR World Magazine, March 1995; *in press.*

Merril, J., Allman, S., Merril, G., Roy, R., "Virtual Heart Surgery: Trade Show and Medical Education." Virtual Reality World, Vol. 2, No. 4, July/August, p. 55-57, 1994.

Merril, J., Allman, S., Roy, R., Merril, G., "Cyber Surgery: Cutting Costs, Sewing Benefits." Virtual Reality Special Report, Summer, p. 39-42, 1994.

Merril, J., Millman, A., Raju, R., Roy, R., "Window to the Soul: A High-Tech Look Into the Eye." VR World, Vol. 3, No. 1, January/February, p. 51-53, 1994.

Merril, J., Brody, F., "Inventing the Future with Virtual Surgery. " Virtual Reality Special Report, Vol. 1, No. 3, Fall, p. 65-70, 1994.

Merril, J., "VR for Medical Training and Trade Show "Fly-Paper"" Virtual Reality World, Vol.2 No. 3, May/June, p. 53-57, 1994.

Merril, J., " The Future of Virtual Reality, Medicine, and the Information Superhighway." Heuristics, Vol. 7, No. 1, Spring, p.33-35, 1994.

Merril, J., Raju, R., Roy, R., "VR Applications in Medical Education." Virtual Reality Special Report; Premier Issue, p. 61-64, 1994.

Merril, J., Roy, R., Raju, R., "Virtual Reality for Trade Shows and Individual Physician Training." Virtual Reality Systems, Vol. 1, No. 3 Spring p. 40-44, 1994.

Merril, J., Roy, R., Merril, G., Raju, R., "Revealing the Mysteries of the Brain with VR." Virtual Reality Special Report, Vol. 1, No. 4, Winter, p. 61-65, 1994.

Merril, J., Preminger, G., Babayan, R., Roy, R., "Surgical Simulation Using Virtual Reality Technology: Design, Implementation, and Implications." Surgical Technology International III, 1994.

Merril, J., "Surgery on the Cutting-Edge: Virtual Reality Applications in Medical Education." Virtual Reality World, Vol. 1, No. 3 & 4, November/December, p. 34-38, 1994

Merril, G., "Design and Implementation of an Interactive Theater," DC Dispatch, publication of the International Television Association, February 1993.

Merril, J., Allman, S., Merril, G., Roy, R., "Virtual Heart Surgery: Trade Show and Medical Education." Virtual Reality World, Vol. 2, No. 4, July/August, p. 55-57, 1994.

Merril, J., Allman, S., Roy, R., Merril, G., "Cyber Surgery: Cutting Costs, Sewing Benefits." Virtual Reality Special Report, Summer, p. 39-42, 1994.

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Merril, J., Higgins, G., Raju, R., Milman, A., Roy, R., Merril, G., "A Virtual Reality Swiss Army Knife: An Authoring System for Developing Everything from Neurosurgical Training Applications to Video Games," VR World Magazine, March 1995; *in press*.

Merril, J., Merril, G., Raju, R., Millman, A., Meglan, D., Preminger, G., Roy, R., Babayan, R., "Photorealistic Interactive Three-Dimensional Graphics in Surgical Simulation," Interactive Technology and the New Paradigm for Healthcare, Vol,. 18, p. 244-252, 1995.

B. <u>Invited Presentations</u>

Merril, J., "Real World Applications, Part II." Virtual Reality and Medicine: The Cutting Edge, New York Hilton Hotel, NYC, September 8-11, 1994.

Merril, J., "Virtual Reality Surgical Simulator." Interactive Healthcare 94": Conference & Exposition, Washington, DC, June 2-5, 1994.

"Markets and Business Opportunities for Virtual Reality Medical Technology" Emerging Medical Technologies Annual Conference, Newport Beach, CA. March 28, 1995.

"Application of the Visable Human Data in Surgical Simulation" Interview for a video production by the National Library of Medicine, Bethesda, MD. March 2, 1995.

"Interactive Multimedia: New Applications and Trends -- Virtual Reality and Medicine" invited lecture for Johns Hopkins University School of Continuing Studies, Baltimore, MD. November 3, 1994.

"Virtual Reality Applications in Medical Training and Pre-Operative Planning" International Symposium on Medical Imaging, George Washington University Medical Center, Washington, DC. June 17, 1994.

"Computer Simulations of Biological Systems" presented at the International Conference of Computer-Assisted Imaging of Embryonic and Fetal Development, sponsored by the Developmental Biology, Genetics and Teratology Branch, National Institute of Child Health and Human Development, National Institutes of Health, Bethesda, MD. June 23, 1994.

"Virtual Reality Applications in Medical Visualization" Invited lecture to the Australian medical visualization research community. Silicon Graphics, Inc., Sydney, Australia. September 15, 1994.

"Virtual reality laparoscopic surgical simulation -- pelvic lymph node dissection" Presentation at the International Urological Society Conference. Sydney, Australia, September 16, 1994.

"The future of invasive medical technology." TV interview: ITN/ABC England. August 1994.

"The Future of Medical Education: Practicing Invasive Procedures with Virtual Reality," 66th National Meeting of the American Health Information Management Association (AHIMA), Las Vegas, NV, October 23, 1994.

"Virtual Reality" Session Leader, FOSE Conference, Washington, DC. March 23, 1994.

"Developments in Virtual Reality and Broadcast Television" Address to The National Academy of Television Arts and Sciences. Bethesda, MD. February 16, 1994.

"Virtual Reality & Education: Today's Supercomputer is the Video Game Machine of Tomorrow" Keynote Address, MICROTRENDS '93, The International Communications Industries Association. Orlando, FL. June 27, 1993.

"The Interactive Multimedia Classroom," Lead speaker and panelist. 10th Meeting of Federal Health Communicators, Project Directors, Project Officers, Federal Health Information Centers and Clearinghouses. National Museum of Health and Medicine, Washington, DC. October 5, 1993.

"CD-ROM and Laserdisc Production Techniques," Guest Speaker, National broadcast for Mind Extension University/George Washington University graduate program in Educational Technology. First broadcast November 19, 1993.

"Applying Educational Media and Technology," Guest Speaker, National broadcast for Mind Extension University/George Washington University graduate program in Educational Technology. First broadcast November 5, 1992.